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In this report we present our progress in the integration of an 850-nm VCSEL, its driver, and a mesoscopic diffractive lenslet array onto a single substrate to produce an integrated opto-electronic multi-chip module for signal fan-out and distribution. The diffractive element performs optical fan-out of the output beam from the VCSEL into an array of focused spots at a plane 1,416 ? m from the surface of the VCSEL. This corresponds to 160? m from the surface of the diffractive lens. System design, fabrication, integration, and experimental characterization are presented.

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Yearly status report for the Office of Naval Resarch Young Investigator Program

Mesoscopic Diffractive Optics for Electronic Warfare Applications

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ABSTRACT

In this report we present our progress in the integration of an 850-nm VCSEL, its driver, and a mesoscopic diffractive lenslet array onto a single substrate to produce an integrated opto-electronic multi-chip module for signal fan-out and distribution. The diffractive element performs optical fan-out of the output beam from the VCSEL into an array of focused spots at a plane 1,416 ?m from the surface of the VCSEL. This corresponds to 160?m from the surface of the diffractive lens. System design, fabrication, integration, and experimental characterization are presented.

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I. INTRODUCTION

Densely packed parallel optical interconnects are essential to ease the communication bandwidth bottleneck projected to occur in future electronic warfare environments. To realize dense optical interconnects one must integrate active and passive photonic elements in a simple and repeatable manner. In spite of proven successes in long-haul communication systems, such as fiber optic networks, the extension of optical interconnects to chip-scale systems has received limited attention. A major reason for this is the difficulty in designing, fabricating, and integrating opto-electronic systems on this scale. In this report we discuss our efforts to address these issues.

Our approach to integration in an opto-electronic multi-chip module (MCM) is illustrated in Fig. 1. A single substrate, transparent to the illumination wavelength, serves as a carrier for the electronics, opto-electronics, and optics. In addition, electrical connections between the opto-electronic source and its electronic drive circuitry are patterned onto one side of the substrate and the optical element that provides distribution is attached to the other. This integration lends itself to a through-wafer three-dimensional stacked architecture whose scale is comparable to that of VLSI. Thus, in

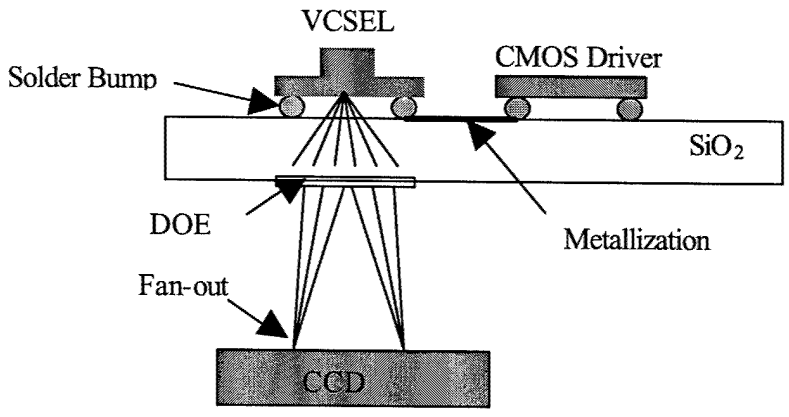


Figure 1. Schematic representation of opto-electronic multi chip module.

comparison to other approaches, system reliability and alignment are improved.

Further, the total distance between the optical source, a vertical cavity surface emitting laser, and the detector plane in our system is approximately one-fifth that of previous demonstrations. This reduction in system length is enabled by the use of diffractive optical elements whose smallest features have sub-wavelength (500nm) dimensions. We now discuss our system integration and present results that demonstrate the utility of our approach.

II. INDIVIDUAL COMPONENTS

A. VCSEL

The VCSEL is one of the most promising sources for high density optical interconnects. In addition to its high modulation bandwidth and surface-normal output, VCSELs can be produced in high-density arrays and operated in parallel. In our demonstration we used a MODE^{TM} Gigalase^{TM} 850-nm VCSEL, which consists of a 1 ? 3 array of VCSELs, each with a different aperture width. The MODE VCSEL chip is compatible with low cost silicon drive electronics, and the operating 850nm wavelength is detectable by off-the shelf Gallium Arsenide detectors. For our demonstration we operated only the center source whose aperture width is 15 ?m. According to vender specifications, the threshold current is 10mA and the maximum optical output power is 16 mW. Experimental characterization of the VCSEL yielded a 16 mA threshold current and an optical power of 10 mW at the operating current of 40 mA.

B. CMOS VCSEL DRIVER

The CMOS laser driver array (CLDA) consisted of a 2 x 1.8 mm^2 40-pad chip that functions as an asynchronous 10-channel driver with ten CMOS-level inputs and ten output currents. The circuit, which operates on the principle that a MOS transistor in saturation acts as a current source, can operate at 700 Mbps and supply a modulation current to the VCSEL of 40mA.

C. DIFFRACTIVE OPTICAL ELEMENTS (DOE)

DOEs are surface relief patterns etched into optical substrates that use diffraction to provide arbitrary control and redirection of light, e.g., off-axis focusing, mode shaping, and beam fan-out. Advances in fabrication have made it possible to fabricate elements whose scale is commensurate with that required for integration with VLSI electronics. Furthermore, DOEs can be etched directly into host substrates using standard photolithography and etching techniques, which facilitates their integration into a manufacturing infrastructure. Our diffractive element was a 40 ? 40 array of 8-phase level lenslets. The design focal length of each lens was 200 ?m at 550-nm illumination over a 50 x 50-?m^2 aperture (*f*/4).

We fabricated the lenslet array using grayscale photolithography. This allowed us to create multilevel structures in a single processing step and alleviate the stringent alignment requirements required for multi-step processing. Our 8-level pattern was written as a gray-level mask onto a high-energy electron beam sensitive (HEBS) glass plate, using direct-write e-beam lithography. The mask was then used to expose a 1.490-?m layer of Shipley AZ 5214 photoresist. Development of the exposed resist in

Microposit 327 MIF created our desired surface, which we hard-baked but did not etch. (The refractive index of the photoresist is sufficiently close to that of the substrate that this did not cause any problems.) The minimum width of our multi-level feature is approximately 0.5 ?m.

III. COMPONENT INTEGRATION

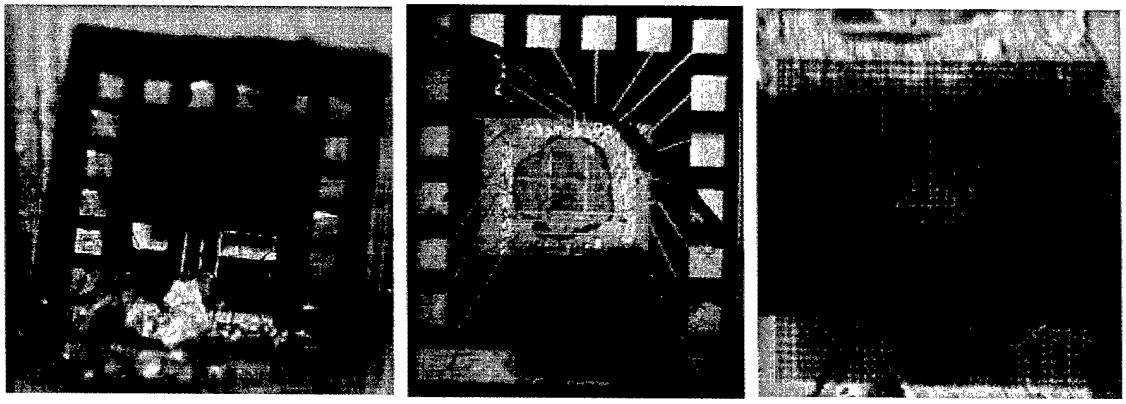
The essential feature of our integration process is the use of a single substrate that serves as a carrier for the individual components. The main advantage of this technique is the monolithic integration of the optical components. To achieve this we used a glass substrate transparent to the illuminating wavelength of the VCSEL, thereby permitting through wafer signal distribution. For demonstration purposes, the DOE was fabricated on a separate glass substrate and finally epoxied to the host substrate. In the case of hybrid integration of optical components, due to refractive index mismatch, we encounter problems of back reflections leading to poor transmission, which lead to an increase in power requirements. For higher level of integration and thus increased system reliability, the DOE can be fabricated directly on the host substrate.

Preparation of the substrate required two metallization steps. In one we provided the electrical connection between the VCSEL and the VCSEL driver and in the other we laid down the indium bumps necessary to flip-chip bond the CLDA and VCSEL array to the substrate. We used traditional lithographic processes to pattern the glass substrate.

We first generated a mask defining the electrical connections between the CLDA and VCSEL. The mask was used to expose a 1.5-?m layer of the negative resist NR7 on the glass substrate, which was hard-baked at 100°C and developed using RD6. In the voids

left by exposed resist we used an e-beam evaporator to deposit consecutive 20-nm layers of titanium and 200 nm layers of gold. The photoresist was dissolved in acetone and served to lift-off the excess gold from the substrate. Definition of the indium bumps was achieved in a similar fashion, except the 6-?m layers of indium were deposited using thermal evaporation. Negative resists like NR7 exhibit negative angle resist profiling which facilitates the lift-off process.

We used an SEC Omnibonder 860 to flip-chip bond the CLDA and VCSEL to the substrate. The Omnibonder can achieve an alignment precision of +/- 5?m. The bonding process was completed using a bond load of 60 grams at 150°C. We also epoxied the lenslet array to the substrate using the Omnibonder to provide accurate placement. The fully integrated MCM is shown in Fig. 2.

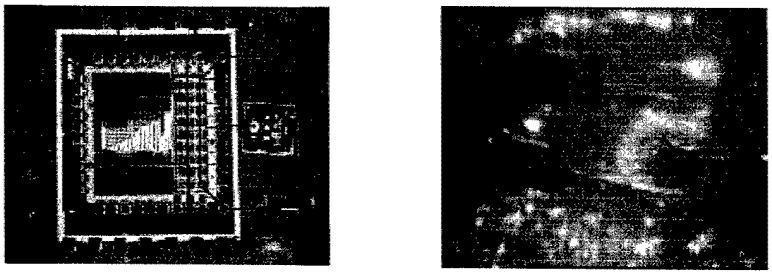


(a) (b) (c)

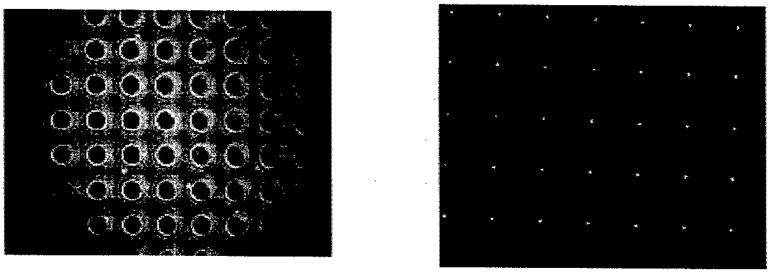
Figure 2. Fully integrated MCM (a) Top view showing CLDA and VCSEL array. (b) Bottom view of CLDA and VCSEL array as seen through lenslet array. (c) Close-up of lenslet array beneath the VCSEL.

IV. TESTING AND CHARACTERIZATION

To test the operation of the MCM, the analog input of the CLDA was set at 3.3 V to achieve a maximum modulation current of 40 mA. The optical output was imaged onto a near-infrared camera mounted and captured using a frame-grabber. We used computer-controlled micro-positioners to scan for the best focus, which was 160 ?m from the surface of the lenslet array. See Fig. 3. We used diffractive elements with 200 ?m designed focal length for 550nm plane wave illumination. Although these elements were designed for a different operating wavelength, their performance in our system is consistent with a diverging VCSEL beam illumination with 850nm wavelength. Further, using our design method and fabrication facilities, we can design application specific diffractive optical elements for future interconnect architectures.



(a) (b)



(c) (d)

Figure 3. Demonstration of VCSEL fan-out. (a) CLDA integrated with 1 x 3 VCSEL array (b) Lasing of multimode 850-nm VCSEL (c) Diffractive lenslet array (d) Image of 5 x 7 array of focussed spots generated 160 mm from DOE surface.

The number of lenslets illuminated depends on the separation between the source and the lenslet array as well as the beam divergence angle. Over the approximately 1.25 mm that the beam travels before it illuminates the element, its

diameter expands to 525 ?m and illuminates approximately 35 lenses. The pitch between spots was measured experimentally to be 55 ?m and the full width at half maximum spot size was 3.5 ?m. We have plotted the relative intensity of the focal spots and reported the spot size. More detailed analysis of distortion and absolute intensity would require a more sophisticated imaging system. Our Infrared camera can barely resolve the spots, and the response is highly non-linear with respect to the absolute intensity. For these reasons, our analysis is limited to qualitative characterization, which is best illustrated by the Fig.4 in the manuscript. We would also like to mention that illuminating the lenslet array with a multimode VCSEL would lead to focal spot spreading along the optical axis and by knowing the mode profile at the surface of the DOE we can tailor the lenslet design using different optimization techniques.

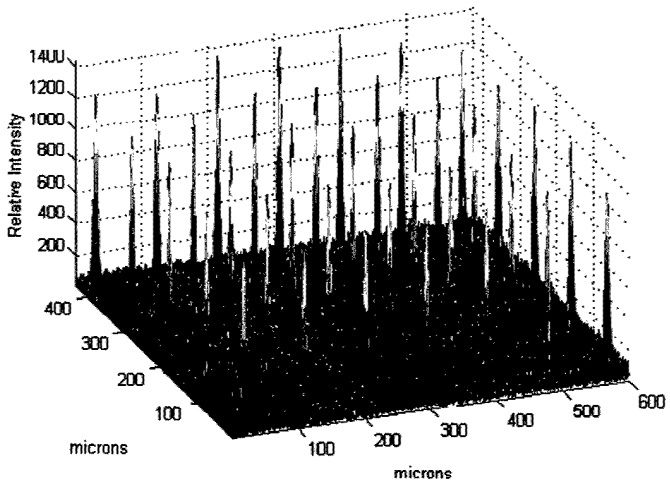


Figure 4. Intensity plot of the focal spots in the image plane.

DISCUSSION

We note that generating fan-out by an array of lenslets involves a space variant approach. To produce greater number of fan-outs requires additional lenses to be illuminated, which can be easily achieved by increasing the thickness of the carrier substrate thus demonstrating the scalability of our approach but at the cot of increasing the volume of the MCM. In our system each additional 100 ?m of propagation distance

illuminates ten additional lenses. One disadvantage, though, is that without modifying each lens there is no way to account for the VCSEL beam shape, which produces a non-uniform fan-out. The fan-out can be apodized but this is not an efficient solution.

Space-invariant designs, on the other hand, can account for beam shape to insure uniformity. Unfortunately, space-invariant designs are not scalable, i.e., each fan-out pattern requires its own design. A space-invariant design also allows us to utilize the entire illuminated aperture to control fan-out. In a space-variant approach the aperture of each lens limits the available degrees of freedom one can use to control each beam. We are currently pursuing space-invariant designs and expect to compare the performance of the two systems within the coming year.

V. SUMMARY

In our progress to date, under this project, we have demonstrated an integrated opto-electronic MCM that uses a glass substrate as a mechanical carrier for the VCSEL, CMOS laser driver, and diffractive optical element. Our approach insures that the system size and integration process is consistent with VLSI technology, i.e., mesoscopic. Our approach insures that the system size and integration process is consistent with the VLSI technology, thus demonstrating the viability of high speed optical interconnects at the chip level. Further, if one uses sapphire instead of a glass substrate as a carrier it would then be possible to fabricate the VCSEL drive circuitry monlithically and thereby eliminate one flip-chip process, thereby simplifying the integration process.